Airborne Thermal Infrared Remote Sensing
Palouse River Basin, WA/ID

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Background

Airborne thermal infrared (TIR) remote sensing has proven an effective method for mapping spatial temperature patterns in rivers and streams. These data are used to establish baseline conditions and direct future ground level monitoring. The TIR imagery illustrates the location and thermal influence of point sources, tributaries, and surface springs. When combined with other spatial data sets, the TIR data also illustrate reach scale thermal responses to changes in morphology, vegetation, and land-use. These data have provided the basis for assessing stream temperature dynamics on a number of rivers across the Western United States.

In 2005, the Washington Department of Ecology and the City of Moscow, ID contracted with Watershed Sciences to provide TIR and true color digital imagery on Paradise Creek, and the North and South Forks Palouse River. The data were collected in support of an ongoing temperature TMDL analysis in the basin. The data were acquired on July 30 and 31, 2005 during the mid-afternoon hours (1:00 to 4:00 PM). Prior to the flight, Watershed Sciences' staff distributed in-stream data loggers (*Onset Stowaways and Tidbits*) in the river in order to provide a quantitative assessment of radiant temperature accuracy (Figure 1).

This report details the work performed, including methodology and quantitative assessments of data quality. In addition, the report presents the spatially continuous longitudinal temperature profiles derived from the imagery. These profiles provide a landscape scale perspective of how temperatures vary along the stream gradient and are the basis for follow-on analysis. Sample images are also contained in this document. The images illustrate some of the thermal features, channel characteristics, and hydrologic processes discussed in the report. The images are not meant to be comprehensive, but provide examples of image scenes and interpretations contained in the image database.

Survey Extent

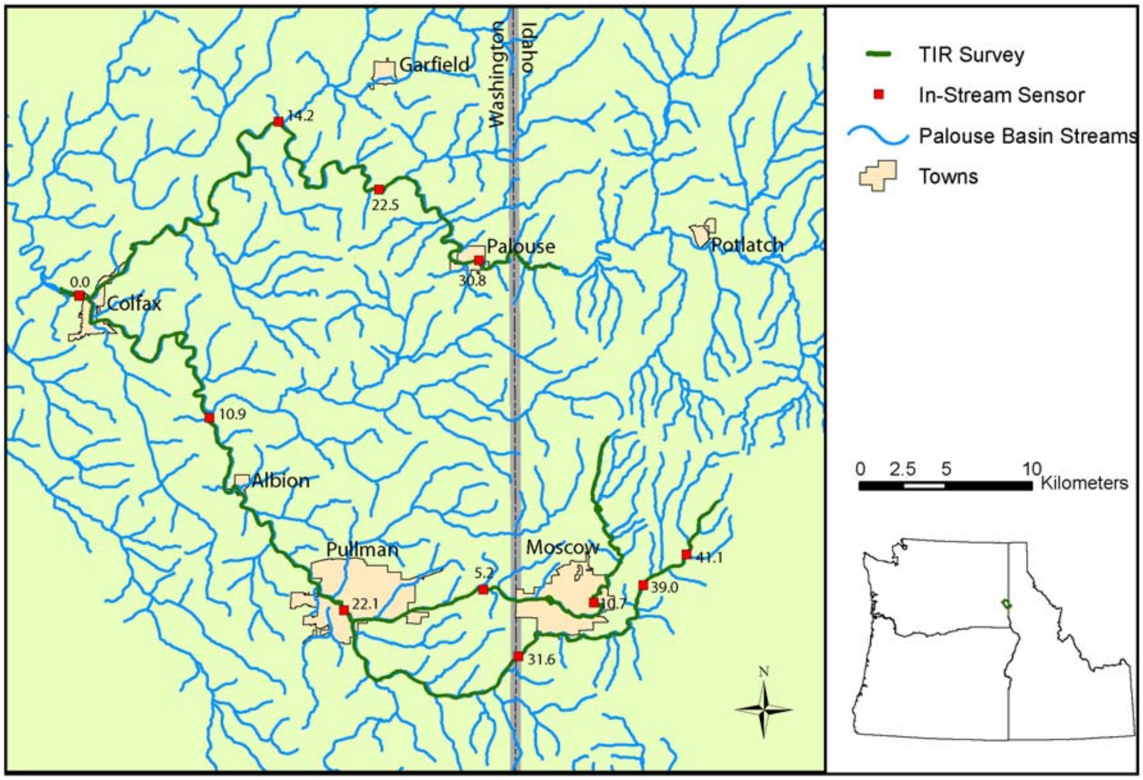

Figure 1 – Map showing the extent of the airborne thermal infrared surveys in the Palouse River Basin, WA/ID on July 30 and 31, 2005. The map also shows the location of in-stream temperature data loggers deployed by WS and labeled by river mile.

Methods

Data Collection

<u>Instrumentation:</u> Images were collected with a TIR (8-12µ) and a true color digital camera mounted on the underside of a helicopter (Figure 2). The helicopter was flown longitudinally along the stream channel with the sensors looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts, which were then converted to radiance values. The individual images were referenced with time and position data provided by a global positioning system (GPS).

Figure 2 - Bell Jet Ranger equipped with a thermal infrared radiometer and high resolution digital camera. The sensors are contained in a composite fiber enclosure attached to the underside of the helicopter and flown longitudinally along the stream channel.

Image Characteristics: The flight plan was designed to capture the width of the active channel at a high spatial resolution. Images were collected sequentially with 40% or greater vertical overlap. The helicopter maintained a flight altitude of 1200 ft above ground level (AGL) for the flight on the North Fork Palouse resulting in an image width of ~234 meters (768 ft) and a native pixel resolution of 0.37 meters (2.4 ft). An altitude of 1100 ft was maintained on the South Fork Palouse River and Paradise Creek. This altitude resulted in an image width of ~215 meters (704 ft) and a native resolution of 0.34 meters (2.2 ft).

Ground Control: Watershed Sciences deployed in-stream data loggers prior to the flight in order to ground truth (i.e. verify the accuracy of) the TIR data. The data loggers were placed at access points along the survey route (Figure 1). The distribution of the in-stream data loggers allowed for checking radiant temperatures at regular intervals over the extent of the survey. Meteorological data including air temperature and relative humidity were collected using an Onset Weather Station located at the Pullman/Moscow Airport.

Data Processing

Calibration: The raw TIR images contain digital numbers that were converted to radiance values based on the response characteristics of the sensor. These measured radiance values were then adjusted using a version of the radiation transfer equation (listed below). The path length attenuation was calculated empirically by comparing the measured radiance to the calculated radiance at each ground truth location. Given the high emissivity of water, the reflection term ($I(T_{reflect})$ was very low and dropped from the equation. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location.

$$I(T_{measured}) = I(T_{object}) * \varepsilon * \tau + I(T_{reflect}) * (1- \varepsilon) * \tau$$

I(Tmeasured)	= measured radiance
I(Tobject)	= radiance emitted at the water surface at given temperature
I(Tatmosphere)	= radiance emitted by the intervening atmosphere
I(Treflected)	= radiance reflected by surrounding objects
ε	= emissivity of water
τ	= path length attenuation

Interpretation and Sampling: The TIR images were analyzed in a GIS environment using a set of custom programs. The analysis consists of sampled radiant temperatures and interpretations of the spatial variations in surface temperatures observed in the images. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file. The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also recorded, with temperatures sampled at their mouths.

Geo-referencing: The images are tagged with a GPS position at the time they are acquired. Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide an accurate index to the location of the image scene. However, due to the relatively small footprint of the imagery and independently stabilized mount, image pixels are not individually registered to real world coordinates. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer (Figure 3).

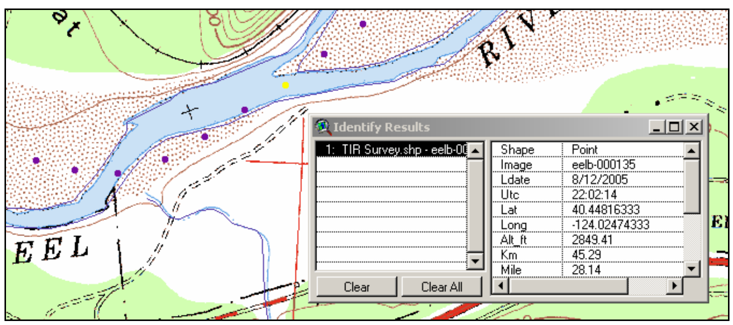

Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition. The point coverage is the basis for follow-on analysis.

Temperature Profiles: The median temperatures for each sampled image were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns. Where applicable, tributaries or other features that were detected in the imagery, but were not sampled due to their small size (*relative to pixel size*) or the inability to see the stream through riparian vegetation are included on the profile to facilitate the interpretation of the spatial patterns.

Geo-Rectification: The TIR images were geo-rectified to real world coordinates using the most recently available digital orthophoto quads (DOQs). The true color digital images were initially oriented using the position and directional information collected on the aircraft. Individual frames were then geo-rectified manually by finding a minimum of three common ground control points (GCP's) between the true color images and the DOQs. An emphasis was placed on finding control points in or near the river channel, with no points in the upland areas. Control points included fixed features such as large boulders and bed rock outcrops. The images were then warped using a 1st order polynomial transformation. TIR images were geo-rectified using the same general methodology with the true color images used as the control layer.

Thermal Image Characteristics

Surface Temperatures: Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperatures. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed; however, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow and can usually be detected in the imagery. Occurrences of thermal stratification interpreted during analysis are identified in the results section for each survey.

Expected Accuracy: Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (~ 4 to 6%). However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.5°C (Torgersen et al. 2001[1]). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.5°C are not considered significant unless associated with a surface inflow (e.g. tributary).

Differential Heating: When the water surface is relatively flat (e.g. pools) with relatively low mixing rates, variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight. Shape and radiant temperature differences distinguish patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike with thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed.

[1] Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

Feature Size and Resolution: A small stream width logically translates to fewer pixels "in" the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures. This was an issue when sampling radiant temperatures on Paradise Creek and the South Fork Palouse River where wetted channel widths were less than 1.5 meters. In some cases, small tributaries were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample.

Temperatures and Color Maps: The TIR images collected during this survey consist of a single band. As a result, visual representation of the imagery *(in a report or GIS environment*) requires the application of a color map or legend to the pixel values. The selection of a color map should highlight features most relevant to the analysis (i.e. *spatial variability of stream temperatures*). For example, a continuous, gradient style color map that incorporates all temperatures in the image frame will provide a smoother transition in colors throughout the entire image, but will not highlight temperature differences in the stream. Conversely, a color map that focuses too narrowly cannot be applied to the entire river and will "washout" terrestrial and vegetation features. The method used to select a color map for the report images attempts to accomplish both. The map is based on using discrete colors to represent the range of water temperatures observed during the analysis based on 1°C or 0.5°C increments and a linear gray scale to represent temperatures above the maximum observed water temperature. Figure 4 provides an example of three different color maps applied to the same thermal image.

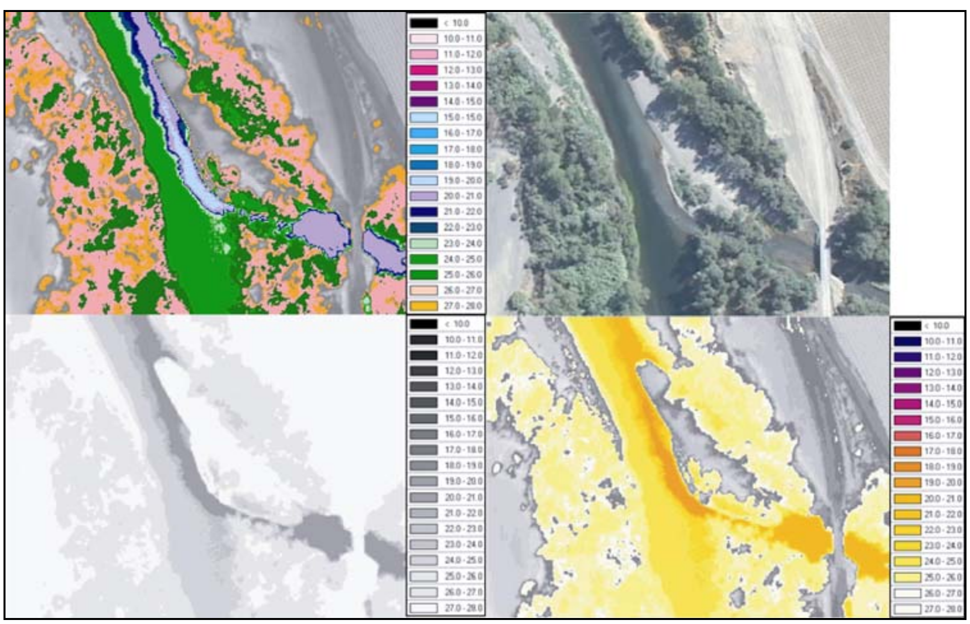

Figure 4 - Example of different color maps applied to the same TIR image.

Image Uniformity: The TIR sensor used for this study uses a focal plane array of detectors to sample incoming radiation. A challenge when using this technology is to achieve uniformity across the detector array. A calibration is performed on the ground, which provides a uniformity correction. However, due to lens distortion and transmission effects, slight radiometric differences can exist between the center and edge of the images. These differences are typically small, with resulting temperature variations ranging from 0.2 to 0.4°C. These differences are not normally an issue, but are noticeable when multiple frames are mosaicked.

Results

Weather Conditions

Weather conditions recorded at the Pullman/Moscow Airport, WA during the dates of the survey.

Date/Time	Temp (*F)	Temp (*C)	RH (%)
7/30/2005			
12:00	88.01	31.12	20.5
13:00	90.22	32.34	20.5
14:00	90.96	32.76	17.1
15:00	93.21	34.01	15.9
16:00	93.21	34.01	15.1
17:00	90.96	32.76	16.3
7/31/2005			
12:00	88.01	31.12	17.1
13:00	91.71	33.17	15.1
14:00	94.73	34.85	15.1
15:00	94.73	34.85	15.5
16:00	93.97	34.43	15.9

Weather conditions were considered ideal with clear skies, air temperatures in the mid 90's (°F), low humidity, and calm winds. (*Picture from 7/30/05*).

Thermal Accuracy

Table 1 summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. In general, the range of temperature differences were consistent with those observed during other surveys conducted in the region over the past six years.

On the North and South Forks Palouse River, the average absolute temperature accuracies were within the desired accuracy of $\pm 0.5^{o}$C. Two additional in-stream sensors were deployed in the South Fork (miles 39.0 and 41.1), but were not used during the calibration and thermal accuracy assessment due to the small size of the stream (relative to image pixel size) at these locations. Audits of kinetic temperatures were taken when the sensor was deployed and retrieved using a handheld digital thermometer. The handheld readings were consistent with the in-stream data logger within the tolerances of both instruments (i.e. $\pm 0.3^{o}$C).

Of the three sensors used in Paradise Creek, two had radiant temperatures that were 1.4^{o}C warmer than in-stream temperatures. Paradise Creek similarly had narrow channel widths and very little visible surface water in the upper reaches. The observed difference between radiant and kinetic temperatures is most likely due to hybrid pixels (i.e. pixels that are a combination of water and terrestrial features) resulting in higher apparent radiant temperatures. Consequently, the differences observed at these two locations are not considered a true reflection of the accuracy of the instrument.

Table 1 - Comparison of in-stream (kinetic) temperatures and radiant temperatures derived from the TIR imagery.

Site	Image Frame	Mile	Time 24 hr	Kinetic ^{o}C	Radiant ^{o}C	Difference ^{o}C
South Fork Palouse River (7/31/2005)						
Colfax Bridge	sfp-000019	0.0	13:25	27.1	27.2	-0.1
Shawnee Bridge	sfp-000334	10.9	13:46	22.7	22.6	0.1
Pullman Bridge	sfp-000655	22.1	14:07	19.2	19.0	0.2
Palouse R. Rd Bridge	sfp-000939	31.6	14:26	18.1	18.9	-0.8
Paradise Creek (7/30/05)						
SF Palouse R.	par-000040	0.0	13:07	18.4	18.1	0.3
Garrison Bridge	par-000231	5.2	13:19	19.7	21.1	-1.4
Moscow Bridge	par-000518	10.7	13:38	21.1	22.5	-1.4
North Fork Palouse River (7/30/2005)						
Colfax Bridge	pal-000026	0.0	14:16	27.3	27.3	0.0
Elberton Bridge	pal-000421	14.2	14:43	27.5	27.1	0.4
Scott Rd Bridge	pal-000625	22.5	14:56	27.5	27.4	0.1
Palouse Bridge	pal-000795	30.8	15:07	25.0	25.2	-0.2

North Fork Palouse River

Longitudinal Temperature Profile

Radiant water temperatures were plotted against river mile to construct a longitudinal temperature profile for the NF Palouse River (Figure 5). The profile also illustrates the locations (by name and river mile) of tributaries and other surface water inflows sampled during the analysis. In addition, the kinetic measurements used to ground truth the thermal imagery are included on the profile and labeled by river mile. The in-sensor located downstream South Fork confluence (Colfax Bridge) was used to ground truth the imagery, but was not included in the North Fork temperature profile.

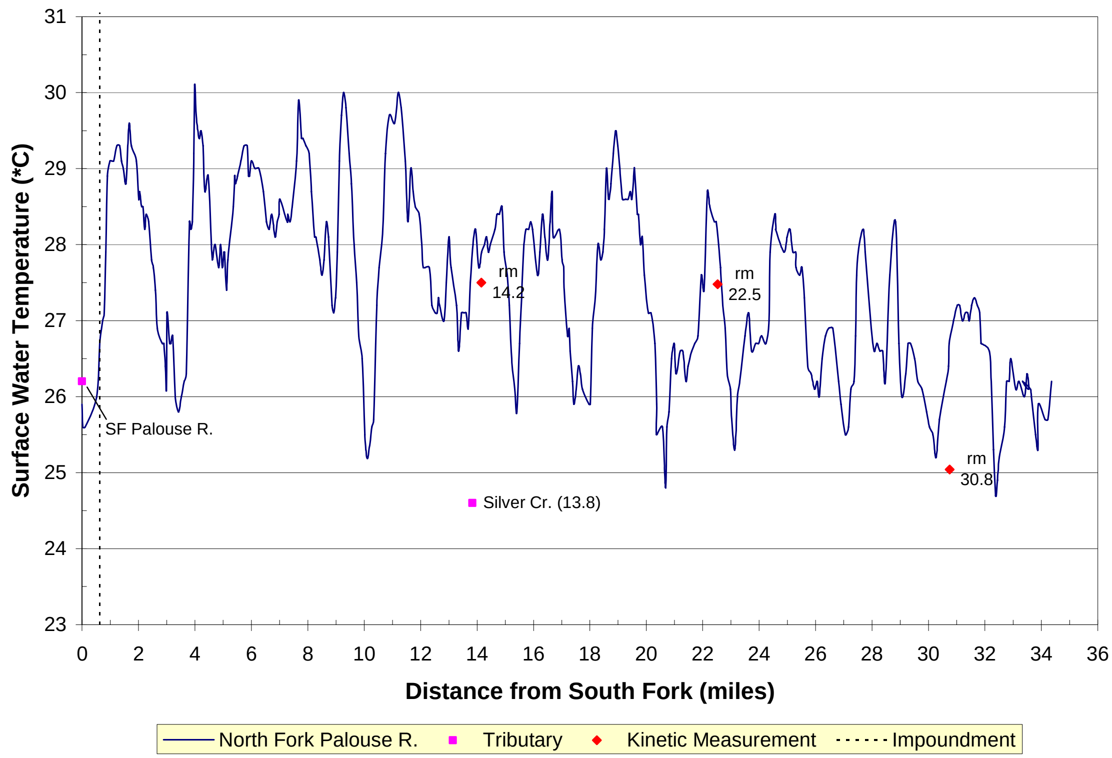

Figure 5 – Radiant water temperatures were plotted versus river mile for the North Fork Palouse River. River miles were calculated upstream from the confluence of the South Fork Palouse River.

Observations and Analysis

Radiant water temperatures in the North Fork Palouse River ranged between 24.7°C and 30.1°C over the course of the 34-mile TIR survey. While temperatures were generally cooler in the upper reaches, the longitudinal temperature profile illustrates a high degree of local spatial variability throughout the survey extent. Silver Creek (mile 13.8) was the only detected tributary with enough visible surface water to obtain a radiant temperature and was observed as a source of cooling to the North Fork Palouse River.

Inspection of the profile shows that radiant temperature changes of more than 1.5°C frequently occurred within longitudinal distances of 0.5 miles. In well mixed systems, rapid decreases in bulk stream temperatures are associated with discharge of cooler water into the stream. In the North Fork, very few surface inflows (i.e. tributaries, irrigation returns, or surface springs) were detected during the analysis. Therefore, the high degree of thermal variability observed in the profile was due to either shallow sub-surface upwelling or intermittent levels of thermal stratification along the stream gradient.

The thermal conditions in the basin during the dates of the TIR survey would be considered extreme by most measures. Air temperatures on the day of the North Fork TIR survey were in the mid-90s with maximum daily air temperatures in the 10 days leading up to the survey ranging between 82°F and 97°F. Flow conditions measured on August 1 ranged from 0.26 cfs (rm 26.0) to 8.38 cfs (rm 8.38).[2] Past TIR surveys under similarly extreme temperature and low flow conditions have also shown a very high degree of thermal variability.[3] These conditions often make it difficult to identify the sources of variability solely through image interpretation.

Inspection of the true color imagery and field observations showed river segments with no obvious mixing and low apparent velocities (*based on wetted channel widths, flow measurements, and flow conditions*). The TIR imagery generally showed warmer radiant temperatures in areas with no obvious mixing and cooler apparent temperatures in riffles and the tail outs of pools and glides. Based on these indicators, differential heating at the stream surface and possible thermal stratification in the deeper pools are probable contributors to the observed spatial temperature variations. The transition from a thermally stratified condition to a well mixed condition can result in apparent temperature decreases in the temperature profile. Similarly, a transition from a partially mixed to a stratified condition can suggest a rapid apparent increase in stream temperatures.

As mentioned previously, four in-stream monitors were deployed by Watershed Sciences in shallow, well mixed areas order to ground-truth the TIR imagery. The water temperatures measured by these sensors closely matched the radiant temperatures derived from the imagery (Table 1). However, seasonal in-stream temperature data collected by the Palouse Conservation District (PCD) and the WA Department of Ecology were consistently less than the radiant temperatures measured by the TIR sensor (Figure 6).

The comparison in Figure 6 illustrates large differences between PCD in-stream monitors and the measured radiant temperatures at miles 18.2, 26.3, and 28.5. However, acceptable comparisons were noted at river miles 22.5 (*WS sensor*) and mile 30.8 (*WS and DOE sensor*). The sensor (*WS Sensor*) located at river mile 22.5 (*Scott Bridge*) was audited upon deployment and retrieval using a handheld digital thermometer with a difference of less than 0.13°C observed between instruments. The radiant temperature accuracy at this location and at mile 30.8 (*WS and* DOE sensors) suggests a good

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[2] *Draft data supplied by Washington Department of Ecology and Golder and Associates.*
[3] *Aerial Survey in the John Day River Basin, OR, Thermal Infrared and Color Videography. Watershed Sciences, Inc. Report to Oregon State University and Bureau of Reclamation, Feb. 2004.*

acceptable calibration of the TIR imagery. However, the differences between the PCD in-stream monitors and the radiant temperatures suggests differences between surface and sub-surface temperatures and a subsequent over-estimation of bulk water temperatures in the longitudinal profile.

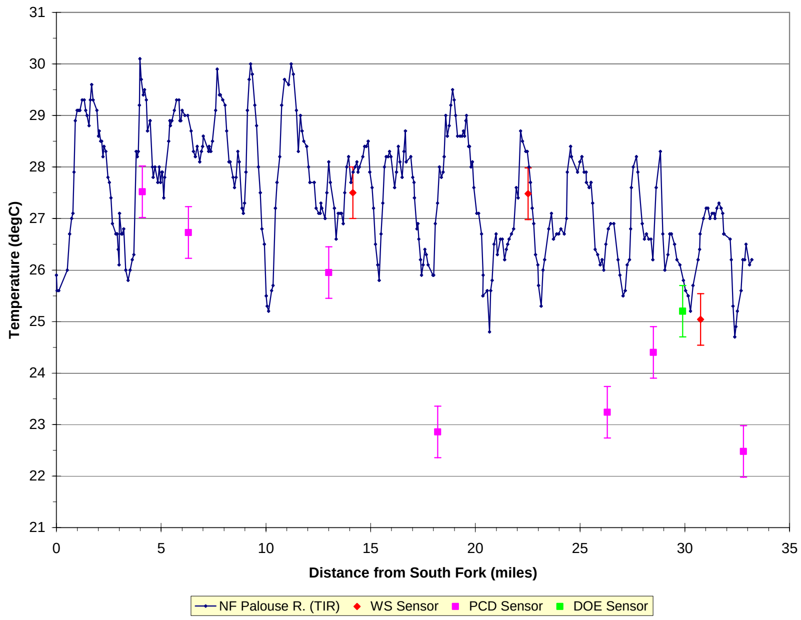


Figure 6 – Longitudinal temperature profile for the North Fork Palouse River compared to in-stream data collected by Watershed Sciences (WS), Washington Department of Ecology (DOE), and the Palouse Conservation District (PCD).

A high degree of spatial thermal variability in small streams is also indicative of the influence of shallow sub-surface discharge on relatively warm streams (*i.e. greater than 24.7°C*). This pattern has been observed during other TIR surveys throughout the region. In these cases, sub-surface upwelling creates a dramatic, but localized decrease in stream temperatures. Stream temperatures then warm up rapidly when exposed to heating processes and mix with the warmer surface water. The interaction of multiple processes such as sub-surface discharges and differential surface heating confounds direct interpretation of the TIR imagery. However, the contribution of sub-surface discharge should not be discounted as a source of thermal variability in the North Fork Palouse River. Follow-on analysis may examine channel morphology (i.e. gradient, channel width, and complexity) in areas where relatively large decreases in stream temperature were observed in the TIR data. These parameters can be used as indicators of the potential for sub-surface exchange in any given reach segment.

The selected images (*next section*) provide some examples of temperature and channel conditions and provide further discussion of the physical processes that may influence the spatial temperature patterns in the North Fork Palouse River.

Selected Images

Images are provided to illustrate thermal features and channel characteristics in the North Fork Palouse River. The plot below (Figure 7) shows the location of sample images contained in this section.

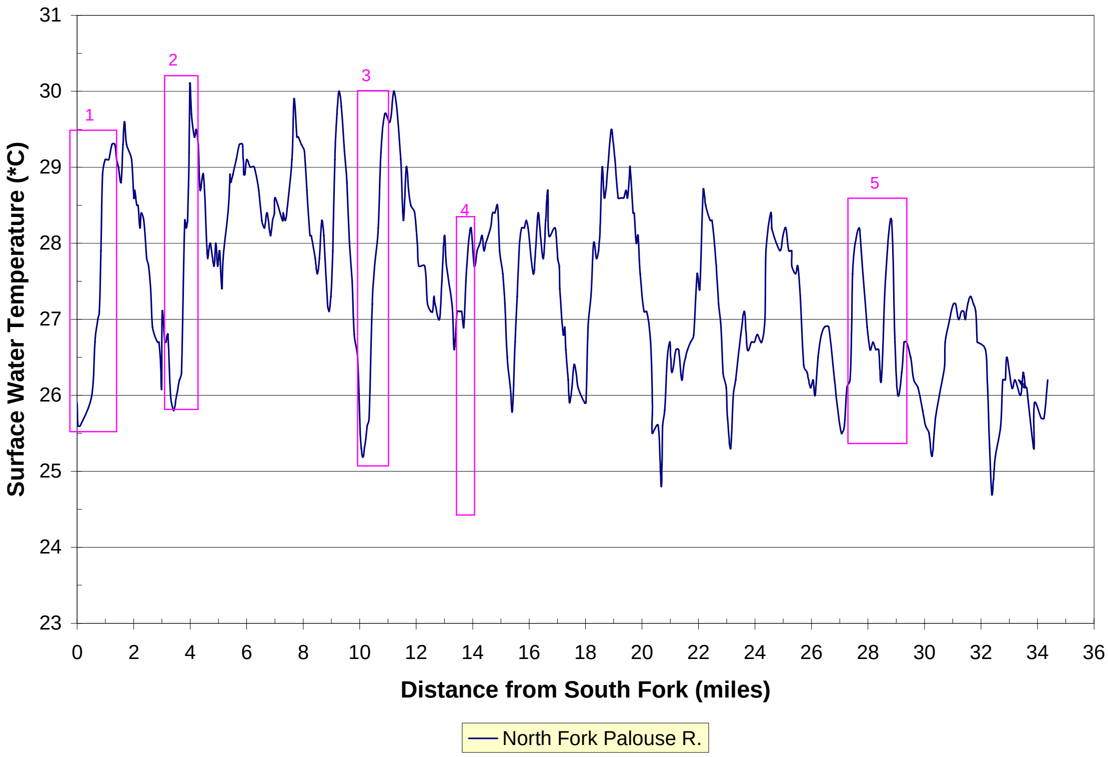
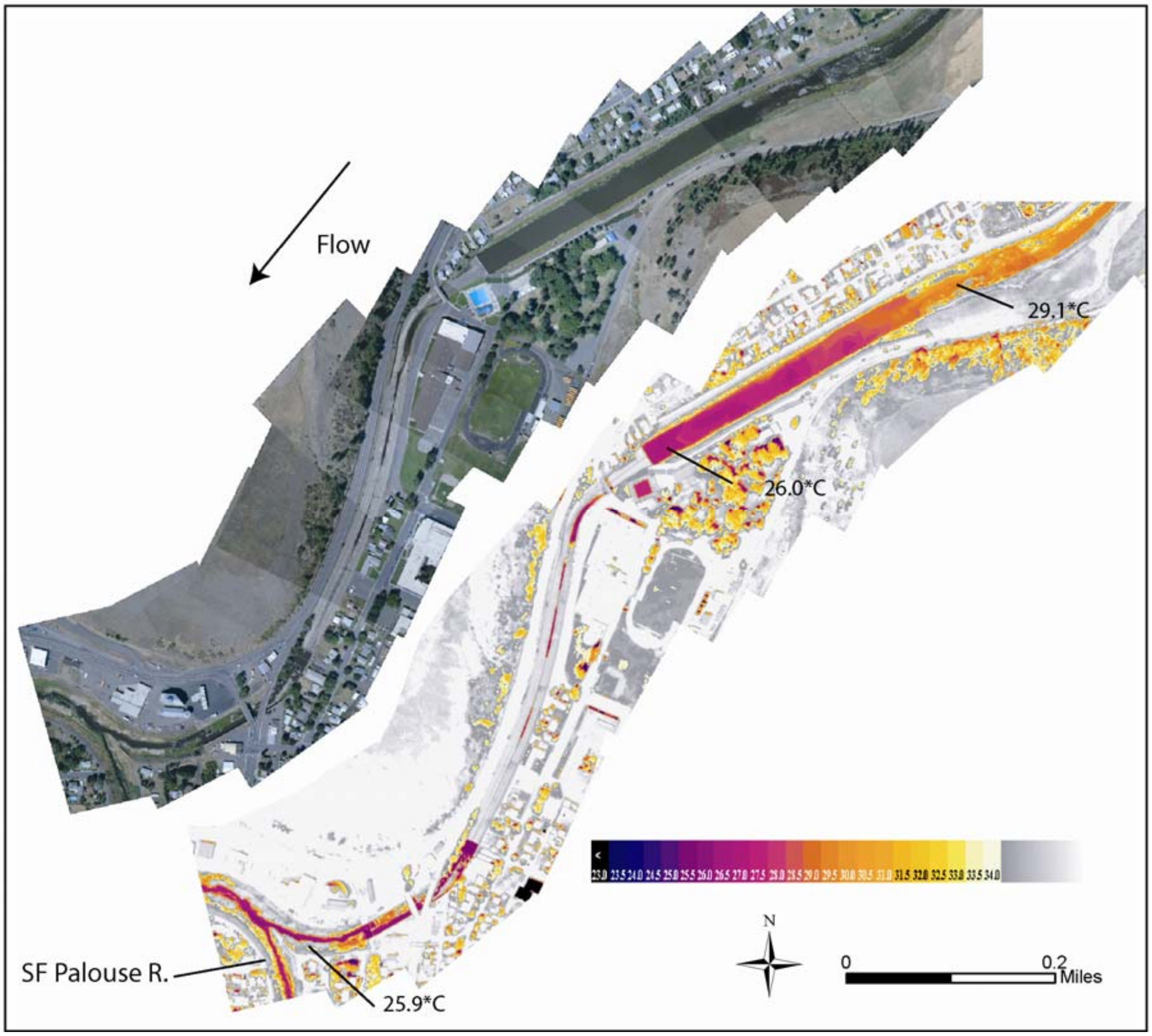
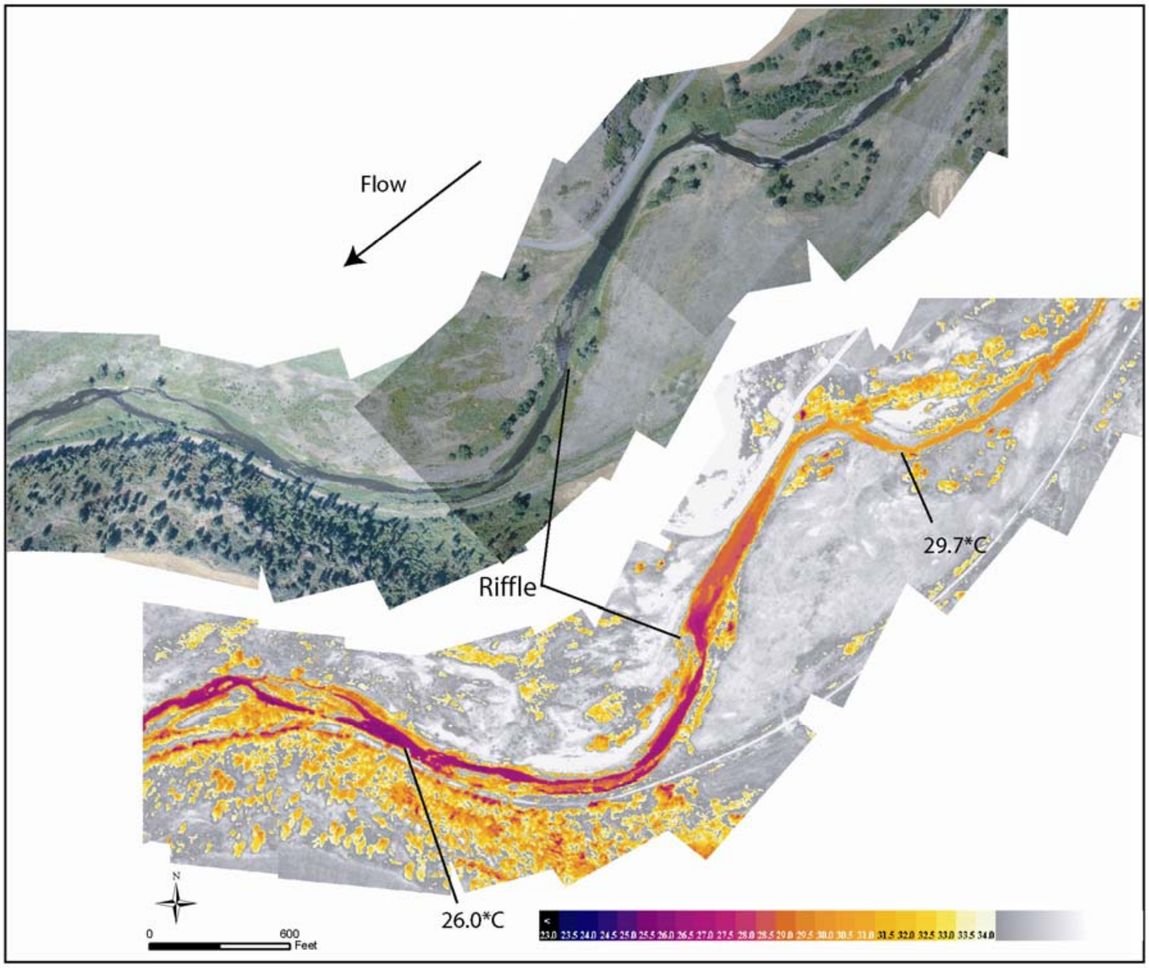


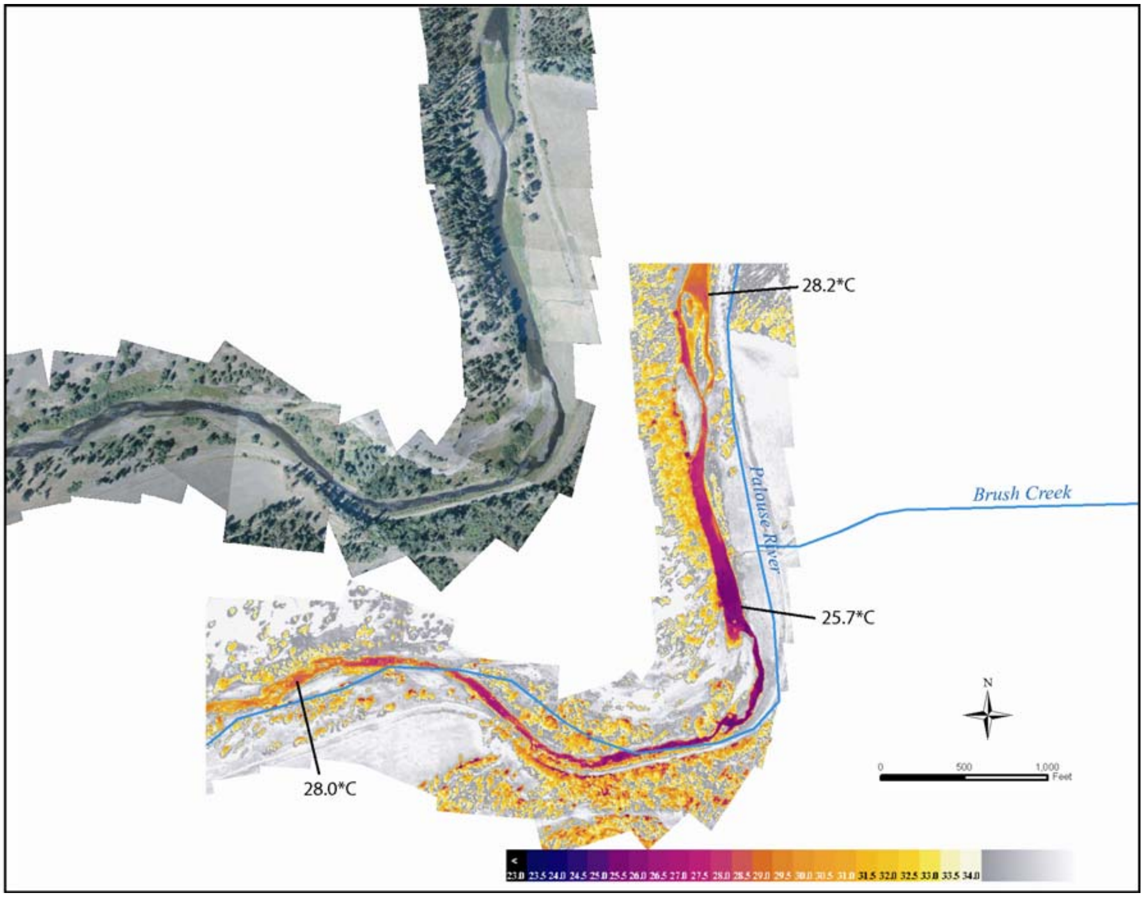
Figure 7 – The magenta boxes show the location of the sample images in relation to the longitudinal temperature profile.



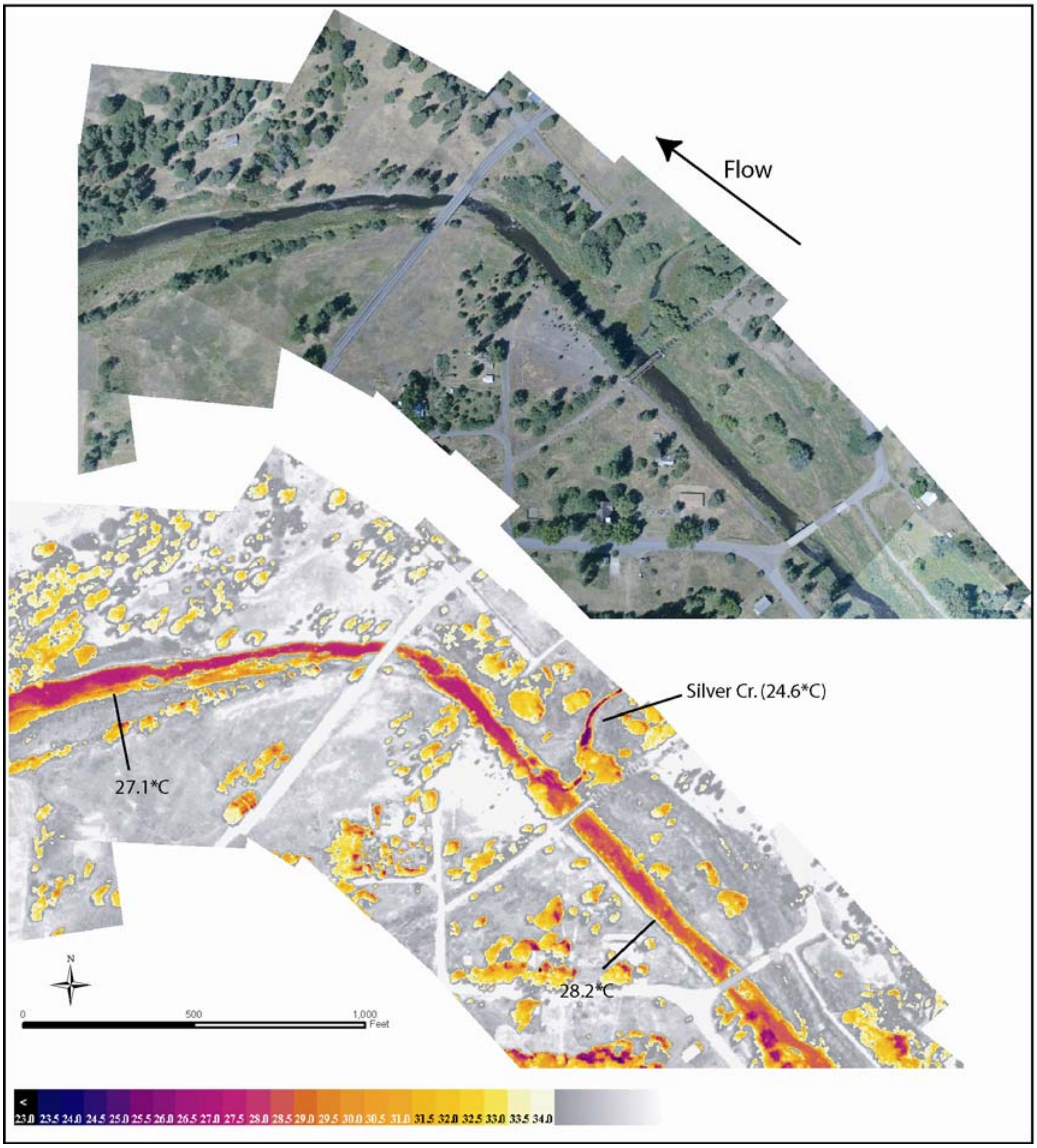
NF Image 1 – True Color (top) and Thermal Infrared (bottom) images showing the NF Palouse River from the mouth upstream to about mile 1.2. The imagery illustrates the channel conditions and range of temperature differences observed near the river mouth. Surface water temperatures were similar between the South and North Forks at the confluence. There was very little surface water was visible in the concrete canal downstream of the impoundment. Surface water temperatures were ~26.0°C immediately above the impoundment, but were considerably warmer (29.1°C) at the upstream end of the pool (~0.3 miles upstream). The visible imagery shows no apparent mixing and some algae on the surface upstream of the pool. These conditions suggest the possibility of thermal stratification in this reach.



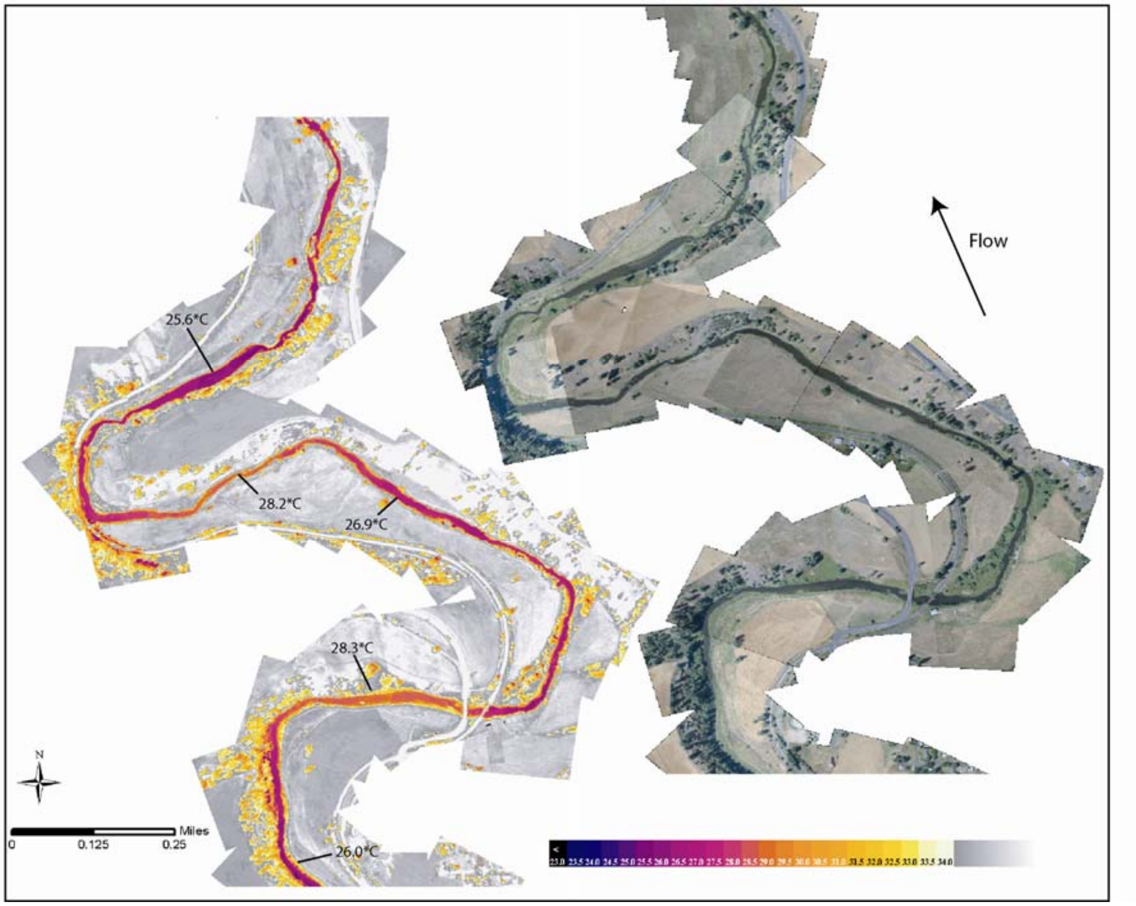
NF Image 2 – True color (top) and TIR (bottom) images showing the NF Palouse River from about mile 3.3 to 4.0. The TIR image illustrates a transition from warm water (~29.7^{o}C) to cooler water (~26.0^{o}C) downstream. The temperature decrease occurs throughout the reach, but is most pronounced at the riffle visible in the center of the image. The sharp decrease suggests either a location of sub-surface discharge or a transition from stratified to mixed condition. The process is not directly apparent from the imagery alone.



NF Image 3 – True color (top) and thermal infrared (bottom) images showing the confluence of the Palouse River and Brush Creek (*mile 9.6 – 10.7*). The 100K stream layer is shown on the TIR image showing the location of Brush Creek. The TIR image shows a decrease in main stem water temperatures (28.2°C -> 25.7°C) starting just upstream of the confluence. However, the cooler water temperatures do not persist and increase rapidly downstream reaching 28.0°C within ~4000 ft (0.74 miles) of the confluence. Although no surface water was visible in Brush Creek, tributary channels are often pathways for subsurface flows.



NF Image 4 – True color (top) and thermal infrared (bottom) showing the confluence of the NF Palouse River and Silver Creek (mile 13.5 – 14.0). Although at the time of the survey surface temperatures in Silver Creek were 24.6^{o}C, this tributary was still a cooling source to the main stem. Silver Creek was the only tributary that had sufficient visible surface water to obtain a radiant temperature sample.



NF Image 5 – True color (right) and thermal infrared (left) images showing the NF Palouse River between river miles 26.6 and 29.1. The thermal illustrates the high degree of spatial thermal variability observed through this reach. Surface temperatures through this reach vary by ~2.7°C (25.6 to 28.3°C). The source of the variability is not directly apparent from the imagery.

South Fork Palouse

Longitudinal Temperature Profile

Radiant water temperatures were plotted against river mile to construct a longitudinal temperature profile for the SF Palouse River (Figure 8). The profile also illustrates the locations (by name and river mile) of tributaries and other surface water inflows sampled during the analysis. Kinetic measurements used to ground truth the thermal imagery are included on the profile and labeled by river mile. A fourth in-stream sensor used to ground truth the imagery of the South Fork Palouse, but was located in the main stem Palouse River and therefore not included in the South Fork profile.

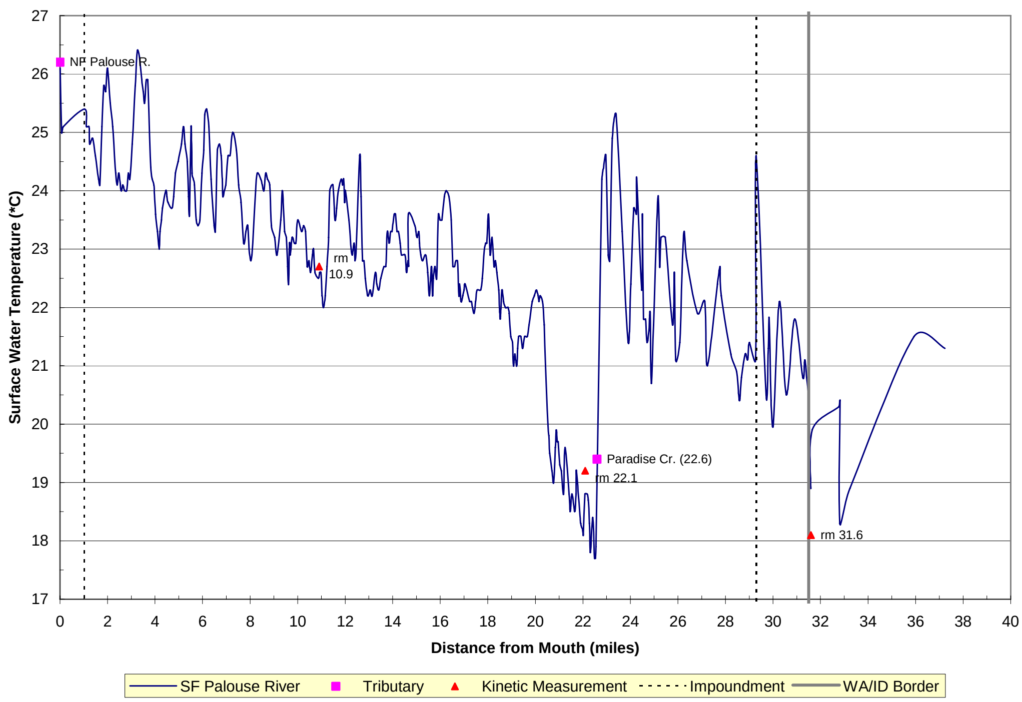


Figure 8 - Radiant water temperatures were plotted versus river mile for the South Fork Palouse River. River miles were calculated upstream from the confluence of the North Fork Palouse River.

Observation and Analysis

Radiant water temperatures in the South Fork ranged from 17.7°C just downstream of the Paradise Creek confluence to a survey maximum of 26.4°C at river mile 3.3 (*upstream of the town of Colfax*). The TIR survey began at the river mouth and continued upstream to near the headwaters (*mile 43.4*). However, upstream of river mile 33.2, the South Fork did not have enough visible surface water to obtain accurate temperature samples. Consequently, the longitudinal temperature profile (Figure 8) extends only to this point while the associated imagery covers the full length of the 43-mile survey. Paradise

Creek was the only tributary (or other surface inflow) detected during the analysis with enough visible surface water to obtain a radiant temperature sample.

Between river mile 33.2 and Paradise Creek, stream temperatures exhibited a general warming trend increasing from ~18.3°C (*mile 33.2*) to a local maximum of 25.3°C (*mile 23.4*). Within this general trend, radiant water temperatures exhibited a high degree of spatial variability with rapid, local changes in radiant temperatures. As mentioned earlier, a high degree of local thermal variability is often a characteristic of comparatively warm streams under low flow conditions. In these cases, relatively small sub-surface discharges can have a dramatic influence on bulk water temperatures. The rapid increase in stream temperature at river mile 29.3 suggests some thermal stratification immediately upstream of a small impoundment observed at that location.

Upstream of Paradise Creek, the South Fork channel was fairly small with wetted widths extending only 1-4 meters. While care was taken to only sample radiant temperatures from clearly visible surface water, the size of the stream compared to pixel size (~0.4 meters) inevitably results in samples with hybrid pixels (*i.e. pixels that integrate water and terrestrial features*). This typically results in increased noise between samples and, in some cases, radiant temperatures that are higher than in-stream temperatures. This fact should be a consideration in interpretation of local temperature patterns upstream of Paradise Creek.

Between the Paradise Creek confluence and the mouth, radiant water temperatures in the South Fork exhibited considerable local variability within an overall downstream warming trend. A notable increase in longitudinal heating was observed between river miles 20.8 and 20.0 with radiant water temperatures increasing by ~3.3°C. Inspection of the imagery revealed that this increase occurs downstream of the Pullman waste water treatment plant and that the channel is exposed through this reach (*as it is through much of its length*). However, no direct mass transfer (i.e. surface or warm water returns) into the river was detected through this reach.

Like the North Fork, the South Fork is impounded in the town of Colfax and almost no surface water was visible in the concrete canal below the impoundment. Surface water was visible again downstream of the canal and had radiant temperatures similar to those in the North Fork (~26.1°C).

Sample Imagery

Images are provided to illustrate thermal features and channel characteristics in the South Fork Palouse River. The plot below (Figure 9) shows the location of sample images contained in this section.

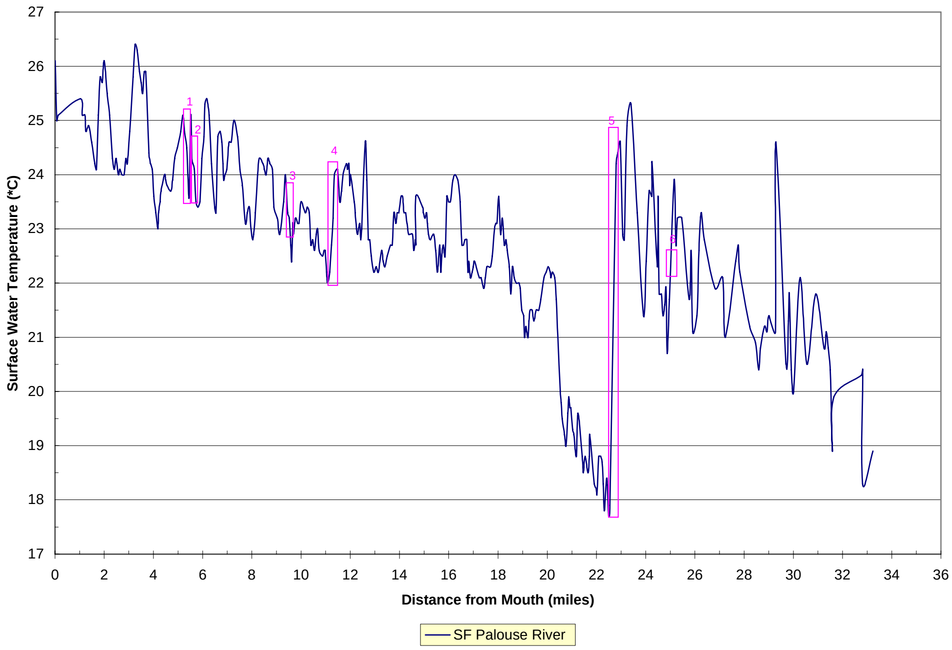
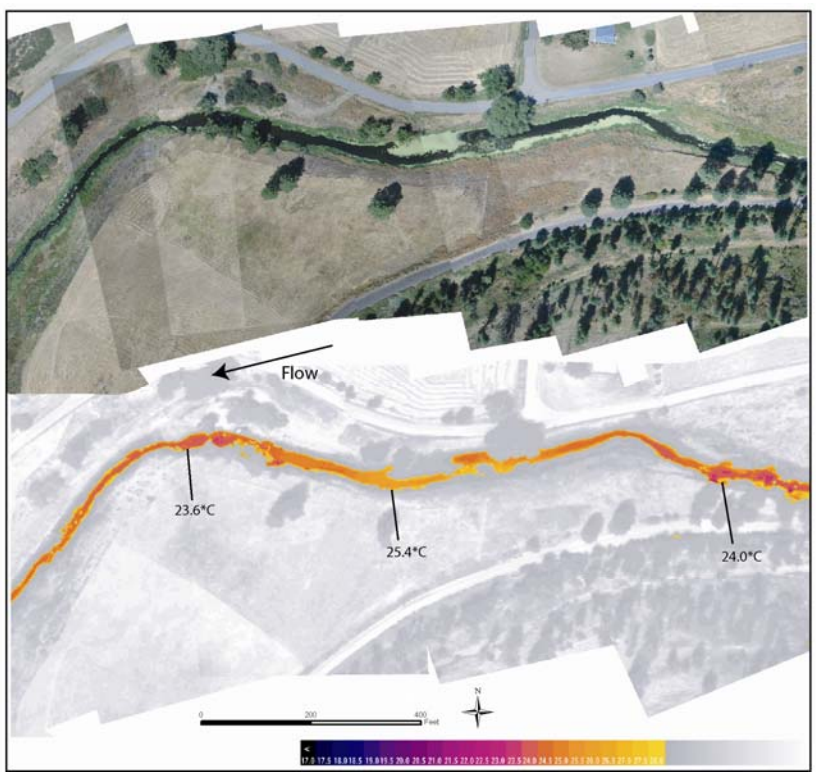
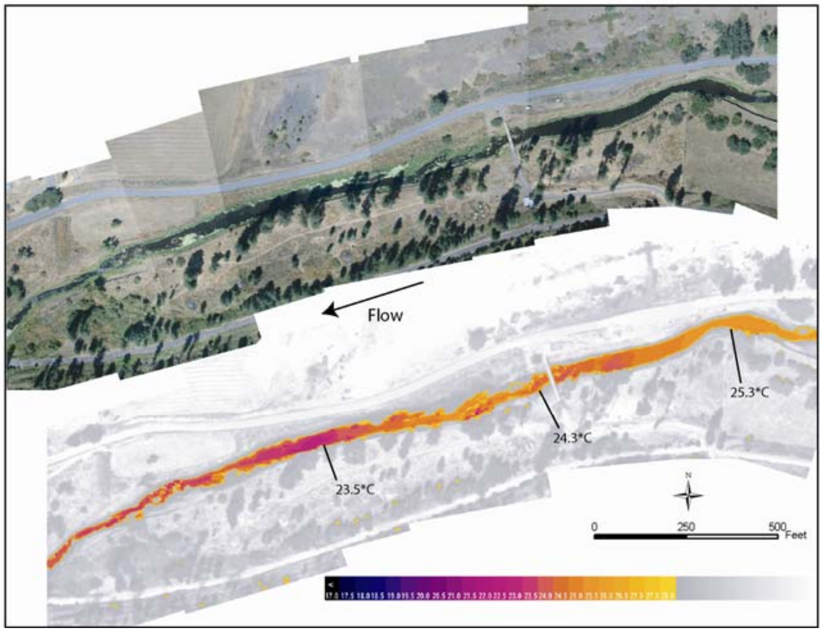


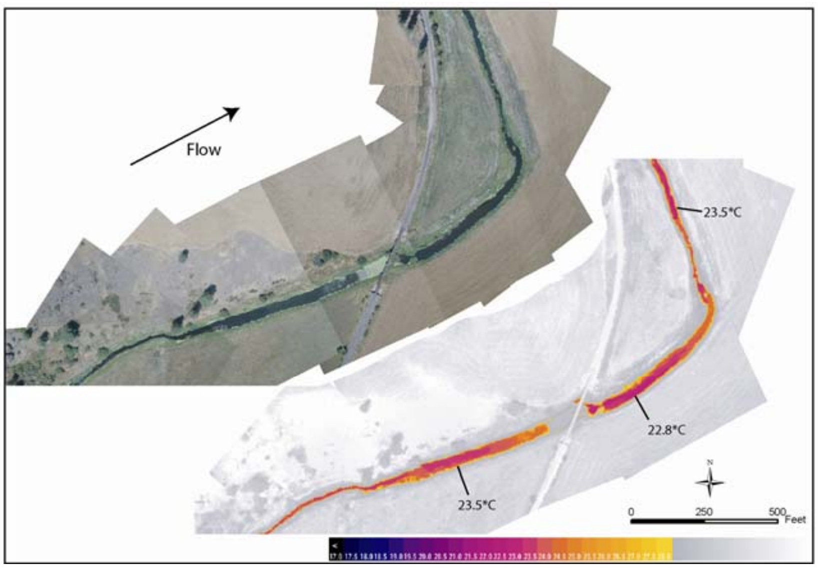
Figure 9 - The location of the sample images (magenta boxes) in relation to the longitudinal temperature profile for the South Fork Palouse River.

SF Image 1 – True color (*top*) and thermal infrared (*bottom*) image showing a section of the South Fork Palouse River near mile 5.6-5.4. The TIR image shows an example of some of the radiant temperature variability observed in this section of the South Fork. In the true color image, the algae on the water surface and absence of riffles suggests flow conditions may be favorable to differential surface heating.

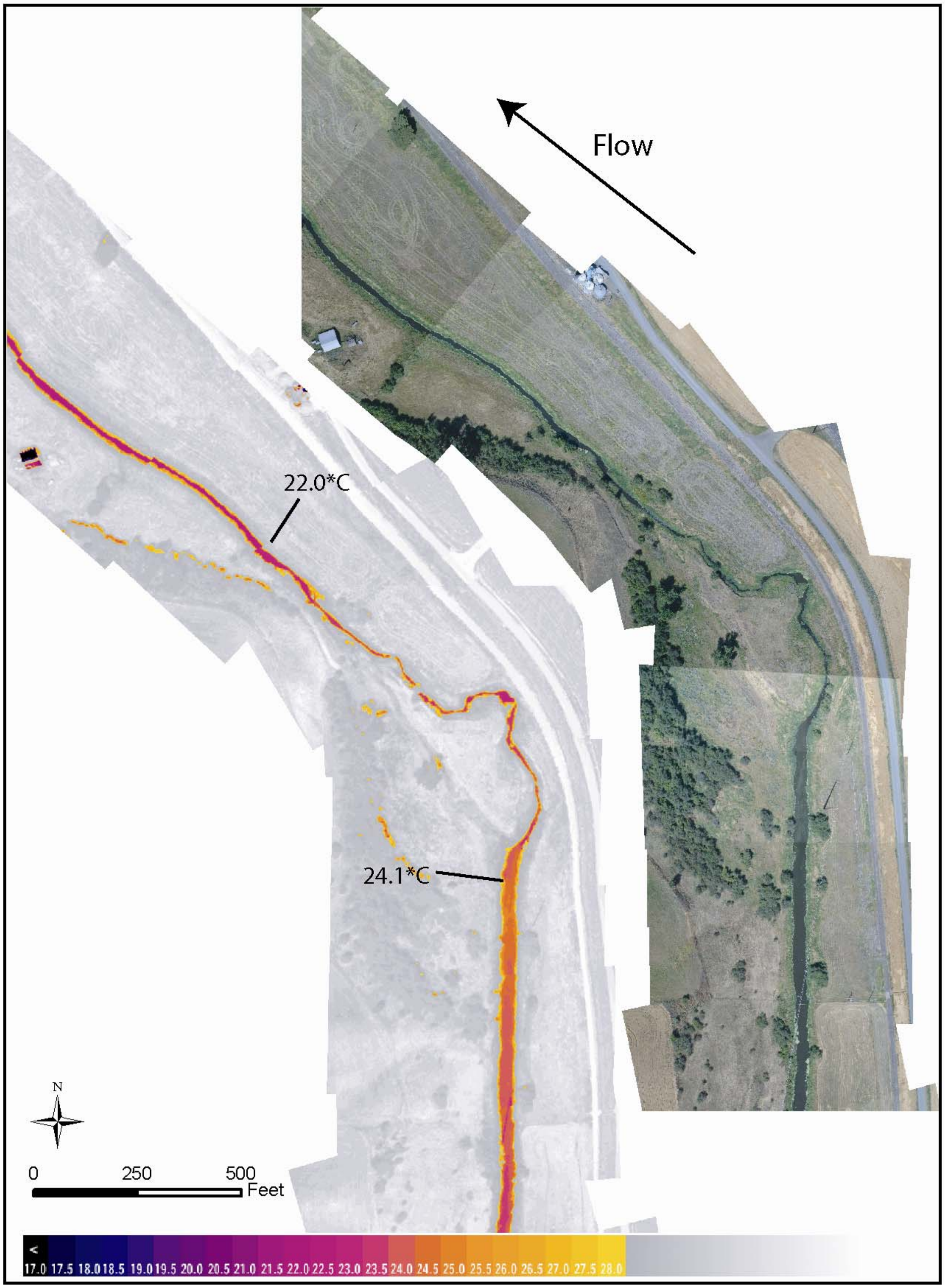




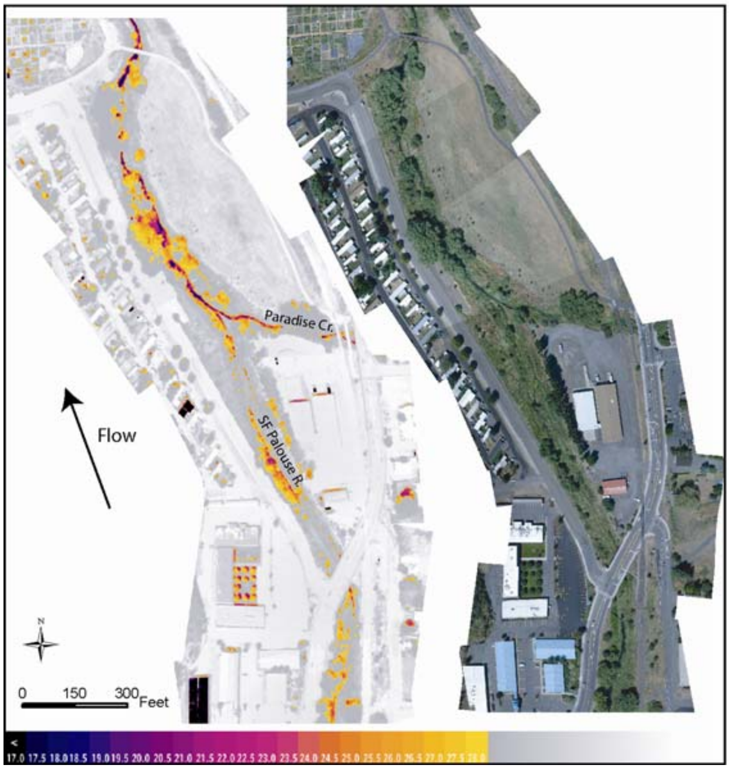
SF Image 2 – True color (*top*) and thermal infrared (*bottom*) image showing the South Fork between river mile 5.7 and 6.1. The TIR image shows a transition from warmer water upstream of the bridge (25.3°C) to cooler water downstream (~23.5°C). The flow conditions, combined with the cooler apparent temperatures downstream of the bridge suggest that differences in surface heating rates contribute to the observed variability. The image also illustrates slight thermal differences (<0.4°C) between image frames.



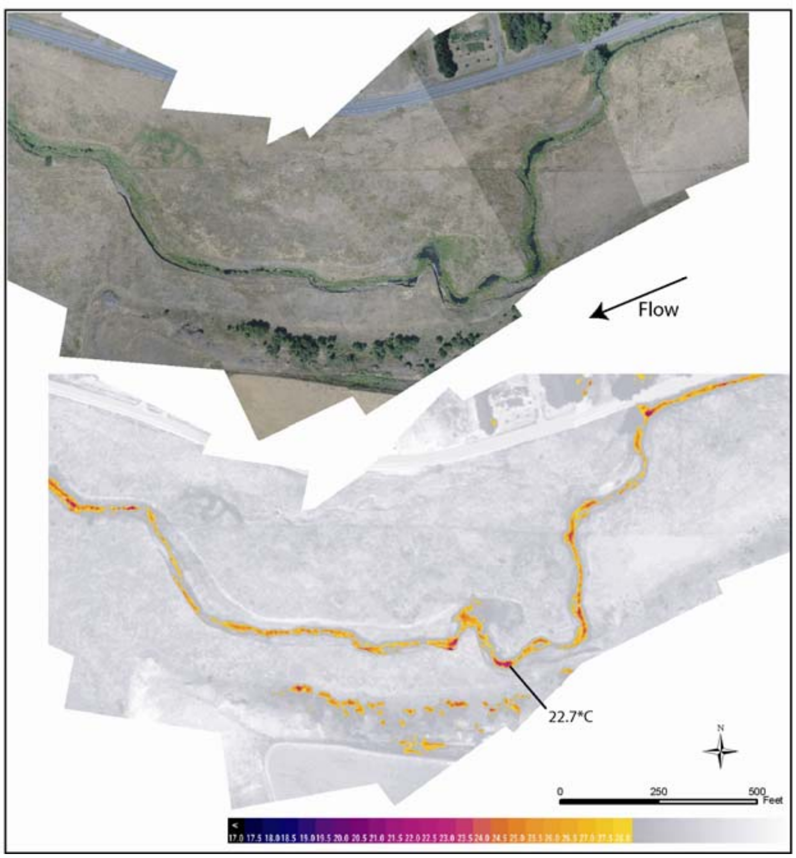
SF Image 3 - True color (*top*) and thermal infrared (*bottom*) image showing the South Fork at river mile 9.4. The TIR image shows slight radiant temperature differences upstream and downstream of the bridge. Algae and flotsam are visible on the water surface above the bridge. The images illustrate the channel and riparian conditions characteristic of the lower South Fork.



SF Image 4 – True color (top) and thermal infrared (bottom) showing the South Fork Palouse River between river mile 11.0 and 11.5. The TIR images shows a decrease in radiant temperatures from 24.1*C to 22.0*C. The source of the decrease is not apparent from the imagery.



SF Image 5 – True color (top) and thermal infrared (bottom) image showing the confluence the South Fork Palouse River (17.9°C) and Paradise Creek. The South Fork channel was considerably smaller upstream of the confluence with wetted channel widths of 1- 4 meters. Radiant temperature samples were limited to locations where surface water was clearly visible and channel widths were better than 2-meters.



SF Image 6 – True color (top) and thermal infrared (bottom) image showing the South Fork Palouse River at mile 25.2. The images illustrate the relatively small wetted channel widths upstream of Pullman. Radiant temperatures were sampled from the pool surfaces.

Paradise Creek

Longitudinal Temperature Profile

Radiant water temperatures were plotted against river mile to construct a longitudinal temperature profile for Paradise Creek (Figure 10). Kinetic measurements used to ground truth the thermal imagery are included on the profile and labeled by river mile. A third sensor was used to ground truth the imagery of Paradise Creek, but was located in the South Fork Palouse River and therefore not included in the longitudinal profile.

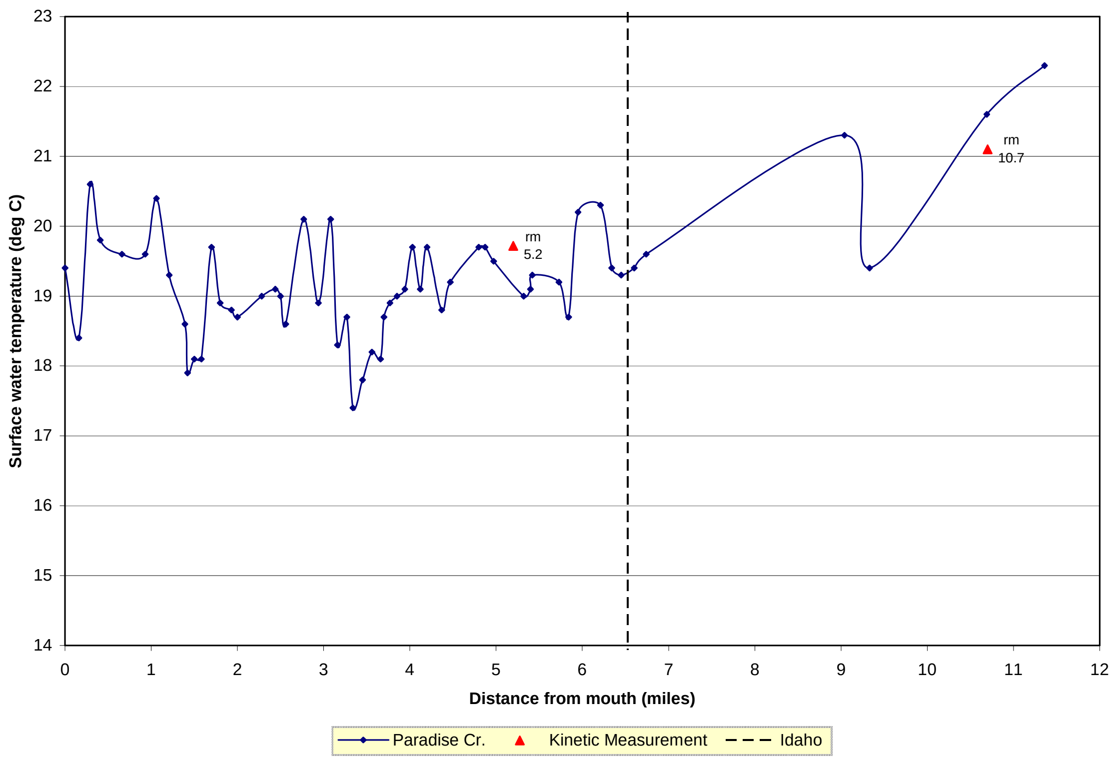


Figure 10 - Radiant water temperatures were plotted versus river mile for Paradise Creek.

Observations and Analysis

Radiant water temperatures in Paradise Creek ranged from 17.4°C to 22.3°C. The longitudinal profile shows considerable variability between radiant temperature samples. The wetted channel width was relatively small (*1 to 5 meters*) throughout the entire extent with some reaches having no visible surface water. Radiant temperatures were sampled where surface water was clearly visible and wetted widths were at least 1.5 meters. This resulted in intermittent sampling throughout the surveyed extent. Although the TIR survey covered 18.6 miles, radiant temperature sampling was only possible over the lower 11.4 miles with only 6 images sampled over the Idaho State Line (*mile 6.5*).

Sample Images

Images are provided to illustrate thermal features and channel characteristics in Paradise Creek. The plot below (Figure 11) shows the location of sample images contained in this section.

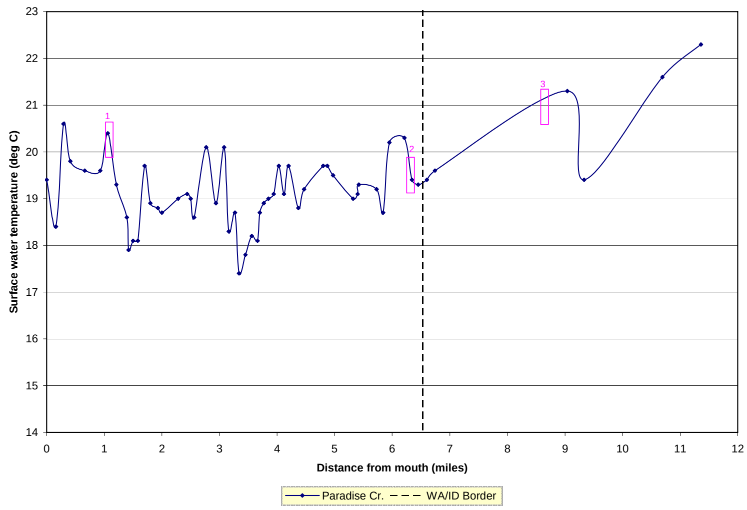
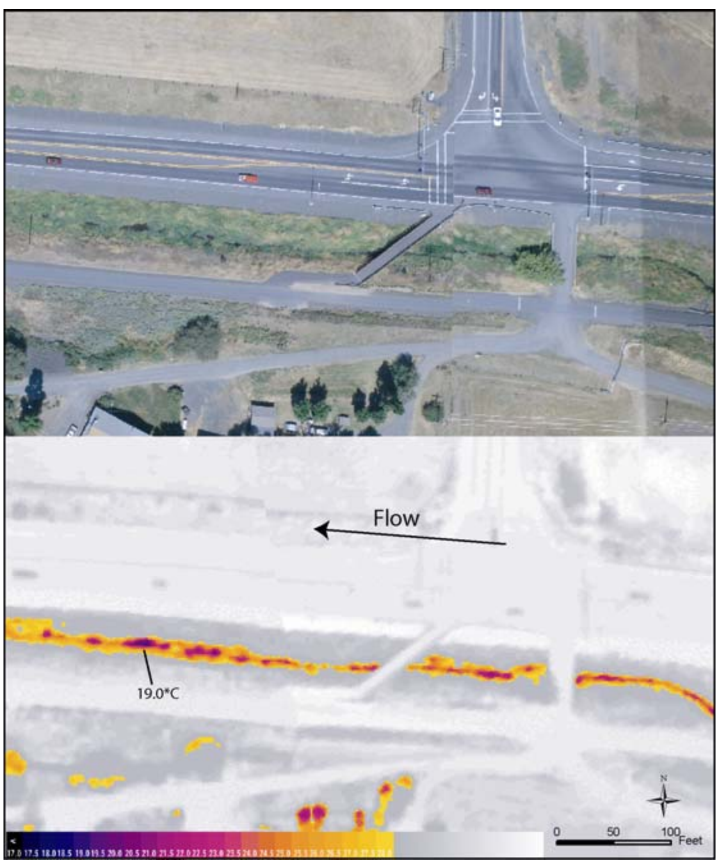
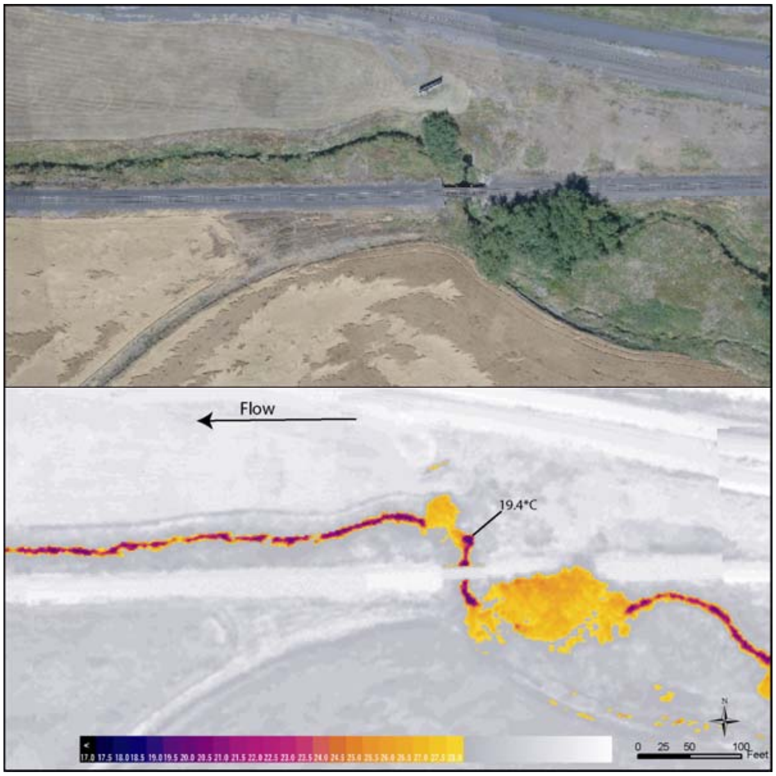


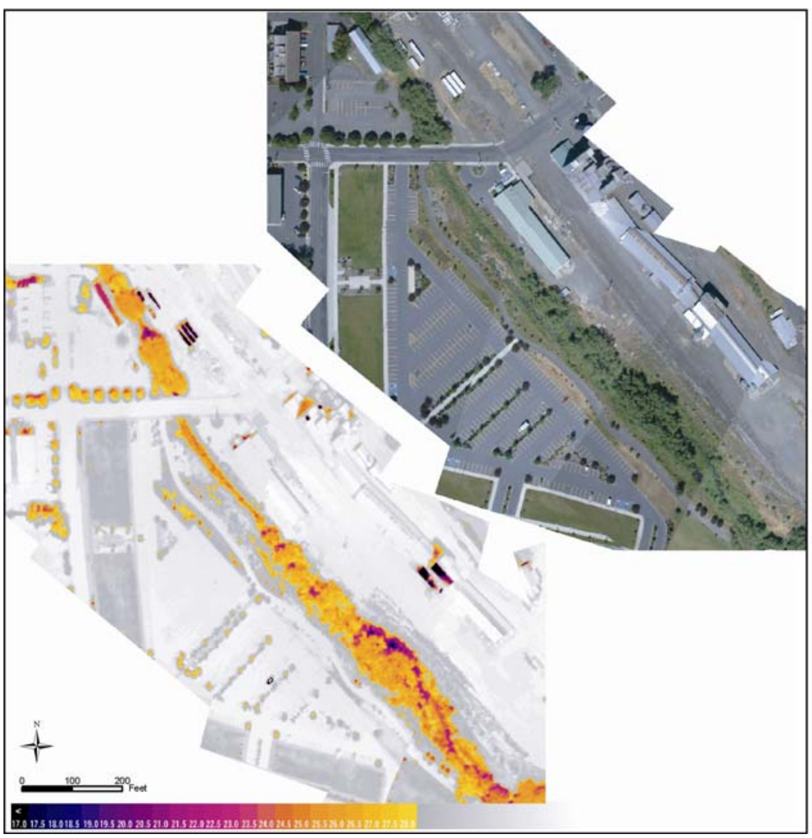
Figure 11 - The location of the sample images (magenta boxes) in relation to the longitudinal temperature profile for Paradise Creek.



Paradise Image 1 – True color (top) and thermal infrared (bottom) image showing Paradise Creek at river mile 1.0. Paradise Creek had relatively narrow channel widths through the entire survey extent with some reaches with no visible surface water. The wetted width at the point of the temperature sample in this image was ~1.8 meters (5.9 ft).



Paradise Image 2 – True color (top) and thermal infrared (bottom) showing Paradise Creek at river mile 6.4. The image shows a reach of continuously visible surface water near the Washington/Idaho border.



Paradise Image 3 – True color (top) and thermal infrared (bottom) image showing Paradise Creek at mile 8.5 on the east edge of the University of Idaho campus. There was almost no visible surface water in Paradise Creek through the campus.

Summary

A TIR survey was successfully conducted on selected streams in the Palouse River Basin. The results showed the average absolute difference between kinetic and radiant temperatures were within the desired accuracy of ±0.4°C. A longitudinal temperature profile was developed by sampling radiant temperatures along the stream gradient. Interpretation of the TIR imagery in relation to the longitudinal profile can provide insight to the physical processes driving the observed temperature patterns.

The TIR imagery is provided in two forms: 1) individual un-rectified frames and 2) a continuous geo-rectified mosaic. The mosaic allows for easy viewing of the continuum of temperatures along the stream gradient, but also shows edge match differences and geometric transformation effects. The un-rectified frames are useful for viewing images at their native resolutions. The native resolution is often better for detecting smaller thermal features. A GIS point layer is included which provides an index of image locations, the results of temperature sampling, and interpretations made during the analysis. The true color digital images are provided as 1-river mile geo-rectified mosaics at 25-cm resolution.

The TIR images and longitudinal temperature patterns illustrate the unique spatial temperature patterns in the North and South Forks Palouse River, and Paradise Creek. Analysis of the data also highlighted many similarities between the surveyed streams. Water temperatures in each stream were relatively warm with minimum measured surface temperatures greater than 17.0°C. Each of the streams showed a relatively high degree of local thermal variability, and spatial temperature patterns were not largely influenced by surface water inflows. Inspection of the imagery on the North Fork Palouse River suggests that differential surface heating in reach segments with lower mixing rates may contribute to the apparent spatial thermal variability observed in the longitudinal profile. The upper South Fork Palouse River and Paradise Creek had relatively narrow channel widths with reaches where no surface water was visible in the 25-cm resolution true color image.

This report provides a description of the methodology used to collect and process the TIR images. This document further provides longitudinal temperature patterns for each surveyed stream and provides some hypotheses with regards to the physical processes driving the observed temperature patterns. These hypotheses and observations are considered a starting point for more rigorous spatial analysis and fieldwork. The TIR imagery and derived data sets provide a spatial context for analysis of seasonal temperature data from in-stream data loggers and for future deployment and distribution of in-stream monitoring stations. Follow-on analysis should also compare these spatial temperature patterns to variations in channel morphology (gradient and complexity) and land-use/land cover. Since some thermal stratification was observed, further interpretations of the TIR images should focus on areas of obvious mixing. The associated high resolution digital images illustrate when surface water was visible in the stream channel and provide a valuable context for further analysis of the TIR images.

Deliverables

Deliverables are provided on a set of DVD's:

Shapefiles and Geo-Corrected Thermal Infrared Mosaics are provided in both Washington State Plane South and UTM Zone 11; NAD83 Geo-Corrected True Color Digital Images are provided in UTM Zone 11; NAD83

Thermal Infrared Images: GRID cell values = calibrated radiant temperature (^{o}C) * 100.

The data are provided on four DVD's with the following directory structure:

TIR – Thermal infrared image mosaic in ESRI GRID Format.
- Non-Rectified,
- Geo-Corrected Mosaic in UTM 11, NAD83
- Geo-Corrected Mosaic in WA State Plane South, NAD27

TrueColor – Geo-corrected 25-cm true color digital images mosaic'd into 1-mile river segments.
Longprofile – Excel file containing the longitudinal profile derived from the TIR images
Survey – Point layer showing image locations, sampled temperatures, and image interpretations.

DVD-1 - NF_Palouse River
DVD-2 - Paradise Creek
DVD-3 - SF_Palouse River 1
DVD-4 - SF_Palouse River 2